ORIGINAL ARTICLES

Assessment of the Performance of an Integrated Domestic Wastewater Treatment System Using Toxicity Tests Incorporated with Physico-Chemical Parameters

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ABSTRACT

Evaluation of an integrated pilot wastewater treatment system was investigated using incorporation of toxicological tests and conventional physico-chemical analyses. The treatment system consisted of three successive units namely; packed bed up-flow anaerobic sludge blanket (P-UASB), inclined plate settler (IPS) followed by a multi-stage roughing fine filtration unit (MSRFF) as a post treatment for the anaerobically treated wastewater. The pilot plant was operated continuously at a hydraulic loading rate of 4 m3/day, average organic loading rate of 2.5 kg COD/m3/day, under ambient temperature ranged from 11-35 ºC and average retention time of 6 h at the P-UASB. Physico-chemical analyses of the treated effluent indicated that the average removal values of turbidity, total suspended solids (TSS), chemical oxygen demand (COD) and biochemical oxygen demand (BOD) were 91%, 94%, 83% and 84%, respectively. Toxicity tests were performed using bioassays with the crustacean water flea, Daphnia magna on samples of both untreated and treated domestic wastewater. Toxicity was assessed using acute (48 h) assays. The acute toxicity test during 36 months study period indicated that the toxicity decreased from 100 %, 87 % and 42 % mortality for the influent wastewater to 45 %, 29 %, and 20 % for the effluent, respectively. Calculated LC50s of the test organism Daphnia magna ranged from 28% to more than 142%. Findings of this study clearly indicated that incorporation of a toxicological test into conventional physico-chemical analyses provided a better evaluation of final discharge characteristics.

Key words: Wastewater treatment, up-flow anaerobic sludge blanket, toxicity bioassays, Daphnia magna, physico-chemical analyses.

Introduction

Domestic wastewater contains a complex variety of organic and inorganic compounds. The composition of wastewater varies significantly both in terms of place and time. Hazard assessment of wastewater is based on physico-chemical parameters e.g. biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH and total dissolved solids. However, during recent years it has become generally accepted that chemical data alone do not allow evaluation of toxic effects. Toxicity bioassays, in contrast to physico-chemical analyses, integrate biological effects of all compounds present and other factors such as bioavailability, toxicants interaction and others. A toxicity bioassay, using the species representing different trophic levels, is a best approach to evaluate the whole toxicity of wastewater (Žaltauskaitė and Vaisiūnaitė, 2010).

Different test organisms are used in ecotoxicological monitoring or bio monitoring to assess biological effects induced by toxicants. Toxicity of wastewater is mainly evaluated with algae or higher plants (Wang and Williams, 1988), luminescent bacteria Photo bacterium phosphoreum (Ince and Erdoğan, 1998), and aquatic vertebrates (fish) (Dwyer et al., 2005). However, the most popular acute and chronic toxicity bioassays are with aquatic invertebrates (especially crustaceans) (Ra et al., 2008; Ghazy and Fayed, 2011) and test batteries (Castillo et al., 2000).

In acute toxicity tests, organisms under a short and frequently intense exposure to a toxic compound or substance show adverse effects. Since effluents are complex mixtures of diverse substances, complexation or speciation of toxicants would be expected leading to enhancement or reduction of toxicity (Gomez et al., 2001). Biomonitoring of effluents allows evaluating their toxic loads by means of toxicity tests in addition with physico-chemical parameters as an integrated approach for the assessment of impacts of discharges in the environment (Wang and Freemark, 1995). The presence of many complex chemicals in the sample makes it difficult to identify, which is the most significant factor causing damage during the testing (Tam and Tiquia, 1994).

The impact of effluents on living organisms is high and governed by several factors, such as a high load of organic matter, heavy metals, and high content of nutrients. Comparative toxicity assessment studies have

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revealed genotoxic properties of wastewater (Helma et al., 1996). Wastewater can also inhibit the growth, feeding rate and reproduction of aquatic organisms and disturb macro invertebrate community structure and functioning (Maltby et al., 2000). In the rivers contaminated by effluents, the fish species richness and composition are observed to be lower than in clean rivers. These effects in fish populations are caused by reproductive dysfunction and recruitment failure (Adams et al., 1992). Accordingly, wastewater must be treated prior discharge into surface water or even reuse.

The up-flow anaerobic sludge blanket (UASB) process is reported to be a sustainable technology for domestic wastewater treatment in developing countries and for small communities. The UASB has been represented as the core technology for an anaerobic wastewater treatment method, widely used for the treatment of medium and high organic strength wastewater. Recently, it has been applied to low-strength wastewater because of advantages such as energy saving and low excess sludge (Takahashi et al., 2011; Abou-Elela et al., 2013a). Sato et al. (2007) revealed that UASB could be the most suitable option in terms of expenses and treatment efficiency for sewage treatment in the warm regions. However, anaerobic treatment alone could not satisfy the regulation for wastewater disposal into surface water or reuse. Accordingly, it is necessary to improve the quality of water and polish up the anaerobically treated effluent using a post-treatment system. Elmitwalli et al. (2001) reported that the anaerobic filter and the anaerobic hybrid system achieved 70% of COD removal efficiency at a hydraulic retention time (HRT) 12 h at 13 °C. Álvarez et al. (2008) reported that the two-stage anaerobic system achieved 49–65% COD removal efficiency at HRT of 9.3–16.9 h at 21–14 °C. Takahashi et al. (2011) proposed low-strength wastewater treatment process that can be used under low-temperature conditions. The process consisted of a UASB reactor as an anaerobic pre-treatment unit and a down-flow hanging sponge (DHS) reactor as an aerobic post treatment unit with a recirculation line.

The aim of this work was to evaluate the performance of an integrated pilot wastewater treatment system consisting of an up-flow anaerobic sludge reactor packed with lamella sheets (P-UASB) followed by an inclined plate settler IPS, then a multi-stage roughing fine filtration unit (MSRFF) as a post treatment. The assessment was carried out using incorporation of toxicological tests and conventional physico-chemical analyses. Acute toxicity tests were evaluated using bioassays with the crustacean water flea, Daphnia magna for 48 h.

Materials And Methods

Description of the treatment system:

An integrated pilot treatment system was used in this study (Abou-Elela et al., 2013b). The system consists of three successive units namely; up flow anaerobic sludge blanket packed with lamella corrugated sheets (P-UASB) and an inclined plate settler (IPS) followed by a multi-stage roughing fine filtration unit (MSRFF) as a post treatment for the anaerobically treated wastewater. Figure (1) shows a schematic diagram for the pilot treatment system.

Fig. 1: Schematic diagram of the pilot treatment system
Operating conditions:

The design parameters and operating conditions of the treatment system are depicted in table (1). The pilot plant was operated continuously for three years at a hydraulic loading rate of 4 m³/day, average organic loading rate of 2.5 kg COD/m³/day and at ambient temperature ranged from 11-35 °C. The system was fed with domestic sewage after coarse screening to prevent clogging and damage caused by rough suspended solids of influent wastewater. During the start-up period, the flow rate was gradually increased from 2.0 m³/day up to 4 m³/day until it reached the steady state conditions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>P-UASB</th>
<th>IPS</th>
<th>MSRFF-unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed retention time (hrs)</td>
<td>6</td>
<td>2</td>
<td>--</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>1.02</td>
<td>0.65</td>
<td>0.43</td>
</tr>
<tr>
<td>Flow rate (m³/day)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Up flow velocity (m/h)</td>
<td>0.42</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Remarks</td>
<td>Packing material is corrugated plastic sheets with specific surface area Ca. 150 m²/m³</td>
<td>Provide by plastic inclined sheets (60° inclination)</td>
<td>Coarse and fine gravel followed by coarse and fine sand</td>
</tr>
</tbody>
</table>

Sampling sites:

Influent and final effluent samples were collected on weekly basis for almost three years, between August 2010 and June 2012 for physico-chemical analyses and toxicity testing.

Physico-chemical analyses:

The investigated physico-chemical analyses were: temperature, turbidity, total chemical oxygen demand (CODtot), Biological oxygen demand (BOD5), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonia (NH3), total phosphorous (TP) and hydrogen sulfide (H2S). All the analyses, unless otherwise specified, were carried out according to the American Public Health Association for Examination of Water and Wastewater (APHA, 2005).

Toxicity testing:

Experimental animals and food:

*Daphnia magna* strain that has been successfully grown in the laboratory in synthetic freshwater media (Fayed and Ghazy, 2000), was used as the test organism. Gravid females were transferred at regular intervals to 1-L glass beakers, in which the culture medium; synthetic freshwater medium (pH; 7.9 – 8.3, total hardness; 90 mg/L as MgCO₃, alkalinity; 34 mg/L as CaCO₃, conductivity; 260 μmhos/cm) was renewed three times a week and was checked daily for the release of neonates to be used in starting experiments. In these beakers, the animals were fed three times a week with the green micro alga *Scenedesmus obliquus*. The algal culture was renewed once a week to maintain the algal solution in good condition. The algae and daphnids were kept at a temperature 22±2 °C with a light period of 16 L: 8 D both during culturing and experimental periods.

Acute toxicity tests:

Acute toxicity tests were conducted in triplicates; the daphnid neonates used in the tests were acquired from an individual culture and maintained in a clean room. Three replicates of ten neonates (less than 24 h old) were used for each treatment and control. Groups of 10 daphnids were placed in 250-ml beakers, each containing 100 ml test wastewater and subjected to test conditions for 48 h. Tests were run without food addition. The number of live organisms after the elapse of 48 h was recorded. Control test was run in parallel in triplicates; each control chamber containing 100 ml synthetic freshwater medium. Temperature was maintained at 22±2 °C by automatic heater. A mercury thermometer was used to measure the temperature in test containers. Daphnids were added to each test and control container and the results of daphnid mortality were recorded after 48 h. The results of experiments were acceptable only in cases where daphnids in the control containers were observed to have a mortality rate of less than 10 %.
Data analysis:

The median lethal concentration (LC50) was calculated for the acute tests using _D. magna_. Toxicity results were calculated by probit analyses using Finney's method (1977) and were reported as a concentration resulting in the death of 50% of the test organisms (48 h-LC50) after 48 h. The terminology recommended by Sprague (1969), lethal concentration (LC) was used for survival as given here, represents an interpolation from three or more partial-effect concentrations.

Results:

Physico-chemical characterization of influent and effluent wastewater:

The results depicted in figures (2-10), indicated the performance of the pilot-plant integrated system for raw wastewater and final treated effluent after using the MSRRF-unit as a polishing step. The average influent turbidity values during the study period were 128, 172 and 103.5 NTU, respectively. The effluent residual average values were 12.7, 14.9 and 9.3, respectively as shown in figure (2). The turbidity removal efficiency of the treatment system was more than 90%.

Fig. 2: Average turbidity values of influent and effluent wastewater of the pilot treatment system during the study period

Figure (3) shows the average concentrations of influent wastewater for COD_{tot}, BOD₅ and TSS during the study period. The average concentrations of influent COD₅ during 2010, 2011 and 2012 were 332, 363 and 272 mgO₂/l, respectively, while for BOD₅ values were 212, 218 and 165 mgO₂/l with TSS content of 179, 256 and 152 mg/l, respectively.

Fig. 3: Average concentrations of TCOD, BOD and TSS in influent wastewater during the study period

The corresponding residual average values for COD_{tot} were 71, 62 and 52.3 mgO₂/l, respectively. Whereas the BOD₅ values were 42, 35 and 27 mgO₂/l. TSS values were 14.5, 18.3 and 9.5 mg/l, respectively as shown in figure (4).
Also, the quality of the treated effluent was monitored through nutrient measurements such as nitrogen, phosphorus and reduced compounds as (H$_2$S).

Figure (5) shows the influent average concentrations for total kjeldahl nitrogen (TKN), ammonia (NH$_3$), total phosphorus (TP) and hydrogen sulfide (H$_2$S). Influent concentrations of TKN, NH$_3$, TP and H$_2$S ranged between 32.4 - 38.8 mgN/l, 19.3 - 23.0 mgN/l, 1.9 - 4.8 mg/l and 2.0 - 5.9 mg/l, respectively as shown in figure (6).

Figure (4) shows the average concentrations of TCOD, BOD and TSS in effluent wastewater during the study period.

Figure (5) shows the average concentrations of TKN, NH$_3$, TP and H$_2$S in influent wastewater during the study period.

Figure (6) shows the average concentrations of TKN, NH$_3$, TP and H$_2$S of effluent wastewater during the study period.
Fig. 7: Average removal efficiency of TCOD, BOD, and TSS for the treatment system during the study period

The results depicted in figure (7) show that the system achieved a sustainable and good removal rates of CODtot (78.6 - 83 %), BOD5 (80.2 - 84 %) and TSS (91.9 % - 93.8 %).

Fig. 8: Average removal rate of TKN, NH3, TP and H2S for the treatment system during the study period

Toxicity testing of influent and effluent

From the results of toxicity testing using the water flea, Daphnia magna as a test organism, it was observed that the calculated LC50 values for the toxic wastewater samples during the study period ranged from 28.4 to greater than 100 % for influent wastewater (Fig. 9).

Average mortality of Daphnia magna reached 100 % in influent wastewater, while it decreased to 45% in the treated effluent in the first year of the study. In addition, the mortality decreased from 87 % to 29 % during the second year and from 42 % to 20 % during the third year (Fig. 10).

Discussion:

Assessment of the results obtained during the three years study period revealed that the proposed integrated treatment system is capable for treating low strength domestic wastewater with average organic loading rate (OLR) of 2.5 kg COD/m3/day. Also, the use of packing material in the UASB with active biomass improved the quality of wastewater due to the biofilm developed on the surface of lamella corrugated sheets which increases the surface area and accordingly increases the entrapment of suspended solids. In addition to its physical role for biomass retention and minimization of suspended solids washout, the packing material has some biological activity contributing the reduction of CODtot and BOD5 than using a classical UASB (non-packed) which only achieve (45 % for COD removal) (Abou-Elela et al., 2013 b). In this study, the removal rates of COD, BOD, and TSS reached 85%, 84%, and 94%. The treated effluent is amenable for reuse in restricted irrigation according to the Egyptian Code of Practice (ECP 501/2005) for wastewater reuse. The performance of the integrated system used in this study is similar to that of Chernicharo and Machado (1998) who studied pilot
plant scale system composed of three units. The overall COD and BOD removal varied from 85 to 95% and the concentration of final effluent COD ranged from 60 to 90 mg/l and the BOD and SS values were less than 40 and 25 mg/l, respectively. Similar results have been achieved by Lew et al. (2004) comparing the performance of a hybrid UASB-Filters and a classical UASB reactor for the treatment of domestic wastewater at different operating temperatures (28, 20, 14 and 10 °C) and loading rates.

Fig. 9: Different LC50s calculated by probit analysis for toxic influent wastewater samples during the study period

Fig. 10: Average mortality of *Daphnia magna* in influent and effluent wastewater
Little nutrient removal may be expected in an anaerobic system treating domestic wastewater, as reported by Moawad et al. (2009). The reason of the low nutrient removal is that during the anaerobic process, organic nitrogen and phosphorous are hydrolyzed to ammonia and phosphate, which are not removed from the system and in consequence, their concentration increases in the liquid phase. Sulfur compounds exist as sulfides in anaerobic systems effluent treating domestic wastewater. The effluent total sulfides concentration greatly depends on influent sulfate concentration and sulfate reducing bacterial activity inside the reactor (Khan et al., 2011). In our study, the use of MSRFF improved the nutrient removal such as TKN, NH₃, and TP to 41.4 % - 57.8 %, 33.5 % – 58 % and 48.7 % to 67.0 %, respectively. This may be attributed to that biological sand filter systems is a biofilm driven process which established on sand grains and accommodate microorganisms that are responsible for biotransformation, biodegradation, mineralization and nutrient assimilation processes involved in wastewater purification (Liu et al., 2009). Phosphorous removal is due to absorption, ionic exchange and adsorption (Achak et al, 2009). Also, H₂S removal is attributed to partial sulfides oxidation to elemental sulfur. This is carried out by high rate micro-aerobic process on the surface of sand and gravel in the MSRFF-unit, where sulfides are oxidized back to sulfate and resulted in low concentrations of H₂S in the final effluent. These results are in agreement with Khan et al. (2011).

Toxicity assessment using Daphnia magna in our study showed that, the treatment system proved to be capable of reducing the toxicity of domestic wastewater to the safe limits. Different test organisms are used in ecotoxicological monitoring or bio monitoring to assess biological effects induced by toxicants (Moriarty, 1999). The existence of sub lethal effects in exposed organisms has been used as an advantage in monitoring strategies for early alert of toxicity (Kendall et al., 2001). In acute toxicity tests, organisms under a short and frequently intense exposure to a toxic compound or substance show adverse effects (Newman and Unger, 2003). Since effluents are complex mixtures of diverse substances, complexion or speciation of toxicants would be expected leading to enhancement or reduction of toxicity (Gómez et al., 2001). Bio monitoring of effluents allows evaluating their toxic loads by means of toxicity tests in addition with physico-chemical parameters as an integrated approach for the assessment of impacts of discharges in the environment (Wang and Freemark, 1995). Daphnia magna was selected as a test organism in our study since it is more sensitive to many toxicants than other test organisms (Ghazy and Habashy 2003). Tyagi et al., (2007) stated that Daphnia magna can serve as a valuable model for bio- monitoring of water pollution and for evaluation of the toxicity of an effluent and risk assessment in an aquatic body, as it is highly sensitive to pollutants. Ghazy and Fayed (2011) studying acute and chronic toxic effects of a waste stabilization pond wastewater on Daphnia magna, found that LC50 of the raw wastewater for D. magna was found to be 21% of the wastewater using the 48h acute toxicity test, while, the effluents from the anaerobic, facultative and maturation steps showed less toxicity than the raw water being 25, 36 and 40% respectively.

Nutrient enrichment and loadings of pharmaceuticals and agrochemicals into freshwater systems are common concerns, especially for water bodies receiving wastewater inputs. Perrodin et al. (2013) stated that hospital wastewaters contain a large number of chemical pollutants such as disinfectants, detergents, and drug residues. A part of these pollutants is not eliminated by traditional urban wastewater treatment plants, leading to a major risk for the aquatic ecosystems receiving these effluents.

Many organic micropollutants present in wastewater, such as pharmaceuticals and pesticides, are poorly removed in conventional wastewater treatment plants (WWTPs). To reduce the release of these substances into the aquatic environment, advanced wastewater treatments are necessary (Margot et al., 2013).

**Conclusions:**

Domestic wastewater is treated using an integrated pilot system that consists of packed up-flow anaerobic sludge blanket packed with lamella corrugated sheets and an inclined plate settler followed by a multi-stage roughing fine filtration unit as a post treatment. The system was operated at a hydraulic loading rate of 6 m³/day, average organic loading rate of 2.5 kg COD m⁻³/day, under ambient temperature and hydraulic retention time of 6 h in the P-UASB. In this study the examination of toxicity properties of influent and effluent was performed using a combination of physico-chemical analyses as well as bioassays aiming to the assessment of their effect on wastewater treatment and the receiving ecosystems. Conclusion drawn from the presented results of physico-chemical parameters removal and Daphnia magna toxicity reduction showed a remarkable performance. The treatment process effectively reduced the concentration of TSS (94 %), COD (83 %), BOD (84 %), TKN (58 %), NH₃ (58 %), TP (67 %) and H₂S (87 %) in all effluent samples during the study period of 36 months. Mortality of Daphnia magna decreased in the treated effluent to 20 %. The results are accepted in toxicity testing confirming good efficiency of the studied pilot-plant treatment system.
Acknowledgment

The authors would like to thank the Science and Technology Development Fund, the Egyptian Academy of Scientific Research and Technology for the research grant (STDF/1088).

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